Low Complexity Adaptive Schemes for Energy Detection Threshold in the IEEE 802.15.6 CSMA/CA

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***Abstract*— IEEE 802.15.6 is a radio interface standard for wireless connectivity of wearable and implantable sensors located inside or in close proximity to the human body (i.e. a Body Area Network). Medical applications requirements impose stringent constraints on the reliability, and quality of service (QoS) in these networks. Radio interference from other co-located BANs or nearby devices that share the same spectrum could greatly impact the data link reliability in these networks. The CSMA/CA MAC protocol as outlined in the IEEE 802.15.6 BAN standard involves the use of an Energy Detection (ED) threshold to determine the status of the transmission channel i.e. idle versus busy. In our previous work, we have shown that the use of such static thresholds negatively impacts the performance of the system composed of multiple co-located BANs, leading to possible starvation or unfair treatment for several nodes. This paper proposes low complexity schemes that can be used to adapt the ED threshold in transmitting nodes of a BAN. The objective is to fairly allow channel access to all nodes regardless of the level of interference that they are experiencing. Simulation results indicate benefits of the proposed strategy and demonstrate improvement in the overall performance.**

Keywords - body area networks, CSMA/CA MAC protocol, interference mitigation, Energy Detection Threshold

INTRODUCTION

A Body Area Network (BAN) consists of multiple wearable (or implantable) radio-enabled sensors that can establish two-way wireless communication with a controller node that is located in the vicinity of the body [1]. Considering the mobile nature of BANs, these networks are expected to coexist with other wireless devices that are operating in their proximity. However, interference from coexisting wireless networks or other nearby BANs could create problems on the reliability of the network operation. For example, when several body area networks are within close proximity of each other, inter-BAN interference may occur. This is mostly due to the fact that there is no coordination across multiple networks. For such scenarios, several mitigation strategies that are applicable to the physical layer have been proposed and studied in [2,3,4]. Uncoordinated Strategies for Inter-BAN Interference Mitigation at the MAC layer assuming a TDMA protocol has also been considered in [8]. Here, we continue our studies on uncoordinated strategies by focusing on the operation of the CSMA/CA protocol in the IEEE 802.15.6.

Consider a system comprised of several adjacent BANs. Each BAN consists of one coordinator and several sensor nodes in a star topology as outlined in the IEEE 802.15.6 standard. A CSMA/CA transmission protocol based on the standard is used for communication between the coordinator and the body sensors. At each BAN, the access to the channel is managed by the coordinator through the establishment of a SuperFrame (SF). According to IEEE 802.15.6 CSMA MAC protocol, time in a SF is divided into slots with duration of 145 μsec. When a node needs to transmit a data packet, a back-off counter (BC) is chosen randomly within the interval [1 CW], where CW ∈ [CWmin CWmax]. The values of CWmin and CWmax depend on the traffic type priority. Then, the channel is sensed for a time period pSIFS (Short Inter Frame Spacing) of 75 μsec to determine whether it is idle. If the channel is determined to be idle for this period, the BC (corresponding to the node) is decremented by one for each idle slot that follows. Once the BC has reached zero, the node transmits the corresponding data packet. On the other hand, if the channel is sensed to be busy, the BC is locked until the channel becomes idle again for the entire duration of a pSIFS.

A node assessment of the transmission channel (i.e. idle vs. free) is done according to the Clear Channel Assessment (CCA) Mode 1 described in the standard document [6]. It involves the use of an Energy Detection (ED) threshold. If the node's receiver detects any energy in the selected frequency channel above the ED threshold, the channel is determined to be busy; vice versa, the idle channel status corresponds to no energy detection above the ED threshold. According to the standard, the minimum ED threshold should be set to values such that the received power is no less than 10 dB above the receiver sensitivity for the lowest data rate within the band of interest. In our previous work, we presented a multi-BAN simulation platform that includes a simplified CSMA/CA protocol based on the IEEE 802.15.6 and analyzed the impact of the ED threshold when several co-located BANs are present [7, 10]. We demonstrated that some performance metric such as average packet delay are heavily dependent on the chosen value of the ED threshold. We also showed that the optimal value for this threshold is very scenario-dependent. Moreover, a static ED threshold could lead to starvation or unfair treatment of several nodes when there are potential interferers in the vicinity. In this paper, we propose adaptive schemes that each transmitting node can use to independently modify its corresponding ED threshold. This adaptation requires sensing average experienced interference by a transmitting node as a measure of the quality of the channel. This information can be used by several low complexity schemes to appropriately adjust the ED threshold at the transceiver.

The rest of this paper is organized as follows. Section II describes our ED threshold adaptation strategies in an uncoordinated multi-BAN environment. Section III briefly describes the scenarios and the metrics that are used to evaluate the performance. Results obtained through extensive simulations are presented and discussed in Section IV. Finally conclusions and future research plans have been discussed in section V.

II. LOW COMPLEXITY ADAPTIVE ENERGY DETECTION THRESHOLD SCHEMES

When the same static ED threshold is used to assess the status of the transmission channel, nodes that are experiencing less interference will have higher chance of accessing the channel and transmitting their data. This will certainly lead into an unfair advantage for such nodes. To balance the channel access probability across all nodes in the system, the ED threshold at each transceiver should be proportional to the level of interference that a given node is experiencing. It is important to note that this is the interference measured at the transmitting node's location. If somehow the interference information at the receiving node was available, clearly much better decisions to access the channel could be made. But this knowledge is not available. We have observed that the higher level of interference at a transmitting node is not necessarily indicative of the high level of interference at the receiver in scenarios consisting of multiple adjacent BANs. This is mostly due to the complex nature of the dynamic on-body and inter-BAN channel characteristics in such systems.

Having a low ED threshold when the interference level is high at the transmitter could result in very conservative operation by the node i.e. few packet transmissions or equivalently higher delays or packet drop rate. On the other hand, a high ED threshold at a transmitter that is experiencing low interference would allow aggressive access to the channel, possibly leading to extra interference for other nodes in the vicinity. Using intelligent adaptive strategies to adjust the ED threshold seem to be an appropriate methodology to mitigate varying level of interference that exists across a multi-BAN system. However, as energy is a significant constraint for nodes in body area networks, an ED threshold adaptation scheme should have a low complexity to avoid any large impact on the node's energy consumption.

Given the main idea expressed above and exploiting channel correlations, we propose the following methodologies to adapt the value of the ED threshold at each node independently:

A) Set the ED threshold equal to the average sensed interference over the past m SuperFrames ($m = 1,2,3, \ldots..$) Repeat the adaptation every m SuperFrames. In other words, for $k = 1,2,3, \ldots.$, calculate ED threshold at SuperFrame n according to:

$$EDT_n = \frac{1}{m} \sum_{i=(k-1)\times m}^{k\times m-1} I_{SF_i} \qquad (1)$$

where k$\times$ $m \leq n < k(m+1)$.

B) Using a sliding window, measure the total interference over m consecutive SuperFrames ($m = 1,2,3, \ldots.$), and set the ED threshold equal to the average sensed interference over the past m SuperFrames. Repeat the adaptation every SuperFrame. In other words, ED threshold at SuperFrame n is calculate according to:

$$EDT_n = \frac{1}{m} \sum_{i=n-1-m}^{n-1} I_{SF_i} \qquad (2)$$

C) Set the ED threshold to be used at SuperFrame n according to the following moving average formula:

$$EDT_n = (1-\beta) EDT_{n-1} + \beta I_{SF_{n-1}} \qquad (3)$$

where EDT_{n-1} is the ED threshold value during SuperFrame $n-1$, $I_{SF_{n-1}}$ is the average sensed interference over the SF $n-1$,and β represents a constant weighting factor between 0 and 1. A lower β adds more weight to the ED thresholds in prior SFs and diminishes the impact of the sensed interference in the current frame. Conversely, higher values of β reduces the impact of ED threshold history. In this scheme, $1/\beta$ is the effective window size of the first order filter represented by the equation (3).

For the above methodologies, the ED threshold at every SF_i is bounded by upper and lower limits of EDT_{max} and EDT_{min} respectively i.e.:

$$EDT_i = \begin{cases} EDT_{max} & if\ EDT_i \geq EDT_{max} \\ EDT_{min} & if\ EDT_i \leq EDT_{min} \end{cases}$$

We are also assuming that the transceiver at each node is capable of sensing and measuring total interference over m consecutive SFs ($m = 1,2,3, \ldots.$). As the functionality to do this operation is currently available in the IEEE 802.15.6 standard (See Clear Channel Assessment (CCA) Mode 1 [6]), no major complexity in terms of additional hardware is expected. The best choice of m in the above schemes depends on the channel coherence time which itself depends on the considered scenarios.

III. SIMULATION SCENARIOS, ASSUMPTIONS & PERFORMANCE METRICS

The first simulation scenario consists of eight stationary

BANs each having 3 on-body sensors and one coordinator node. Stationary scenarios could occur in practical situation like people sitting around a table, in a bus or a classroom. Here, we considered the meeting scenario where eight persons (each wearing a BAN) are sitting around an oval-shaped table (see Fig. 1). The operating frequency of each BAN is considered to be 2.36 GHz (i.e. MBAN frequency band) as adopted by FCC for use in indoor environment [5].

The second simulation scenario also considers eight BANs (again with 3 on-body sensor nodes and one coordinator) moving randomly in a room with a size of 8m × 8m (see Fig.2). For the motion pattern, we have considered a simple version of the random waypoint model to represent people walking around in a building or an office. Other special movement patterns can also be incorporated in our platform if desired.

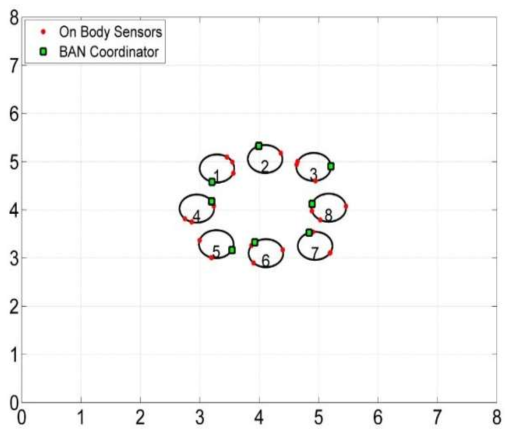

Figure 1. Sample multi-BAN meeting scenario

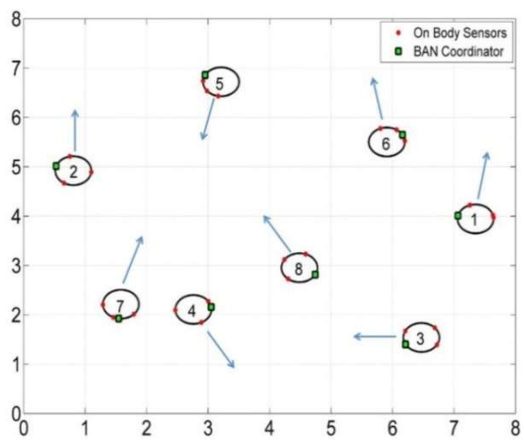

Figure 2. Sample multi-BAN random moving scenario

The traffic model used in our simulation is an i.i.d. Bernoulli with rates between 0 and 1 (packets per SF). Accordingly, traffic load per BAN is defined as:

$$GenRate \times \frac{Packet\ Length}{SuperFrame\ Length} X\ Num\ of\ Nodes\ per\ BAN$$

Where $GenRate$ is the packet generation rate per sensor or equivalently the probability that a sensor has a new packet arrival at the beginning of each SF. The SuperFrame length is set to 10 msec for all BANs, and each packet is considered to have a length equal to 100 bytes. Among the different Modulation and Coding Schemes (MCSs) defined for the ISM band in the IEEE 802.15.6, we have considered MCS2 in our simulations (see table 1).

MCS	Modulation	Information Data Rate [Kbit/sec]	P_{Rmin} [dBm]	$SIR\|_{min}$ [dB]
0	π/2-DBPSK	121.4	-95	-2
1	π/2-DBPSK	242.9	-93	0
2	π/2-DBPSK	485.7	-90	3
3	π/4-DQPSK	971.4	-86	7

Table 1. IEEE 802.15.6 Modulation and Coding Schemes

The performance metrics that have been used to evaluate the proposed ED threshold adaptation are 1) Average Packet Delay and 2) Packet Drop Rate (PDR). Packet delay is defined as the interval of time between packet generation and its correct reception at the coordinator. Using Little's theorem, average packet delay can be computed as follows:

$$\frac{Average\ \#\ of Packets\ waiting\ at\ each\ node's\ queue}{GenRate}$$

To calculate the above, we have simply assumed an infinite size queue (to accommodate the backlogged traffic) along with an unlimited number of retransmissions for the arrival packets at each node of a BAN. This will allow us to evaluate the average packet delay without incurring any packet drops. In order to calculate PDR per node and average PDR across all BANs, limited queues size have also been considered for each node. Packet drop rate per link is computed as:

$$\frac{\#PacketsDropped/Link}{\#PacketsDropped/Link + \#PacketsSuccessfullyReceived/Link}$$

In our simulation scenarios, we have also assumed that all nodes are using the interval associated with the traffic priority level 5 for the back-off counter. This priority level is typically considered for medical applications.

We have evaluated the performance of the three ED threshold adaptation schemes presented earlier using the two scenarios described in this section. The results are presented in the next section. The variable ED threshold values are considered to be in the interval [-84 -60] dBm. The lower bound (i.e. -84 dBm) has been chosen according to the minimum ED threshold criteria stated in the IEEE 802.15.6 standard. The upper bound has been derived from the aggregate inter-BAN interference profile of the scenario taken into consideration.

IV. RESULTS

The average packet delay as a function of the traffic load per BAN for the meeting scenario is shown in Figure 3. Graphs with solid lines refer to performance obtained with a static ED threshold while ones with dashed lines represent the performance obtained using the ED threshold adaptation scheme ‘A’ in Section II for different starting values of the ED threshold. The value of ‘m’ has been considered to be 10. This means that the ED threshold is updated every 10 SuperFrames. As pointed out in [7], for static ED thresholds, the average packet delay is heavily dependent on the exact value of this threshold. The optimal value of the static threshold for the stationary meeting scenario is -62 dBm. This is indicated by the black solid graph in Figure 3. With our proposed adaptive strategy ‘A’, the average packet delay performance is very close to the optimal static value. In addition, the performance is no longer dependent to the initial value of the ED threshold. Similar result is also observed for the random moving scenario as shown in Figure 4. Again, the average packet delay performance results achieved using adaptive scheme ‘A’ are very close to those obtained through the optimal static threshold (-60 dBm in this case) and virtually independent of the initial value of the ED threshold.

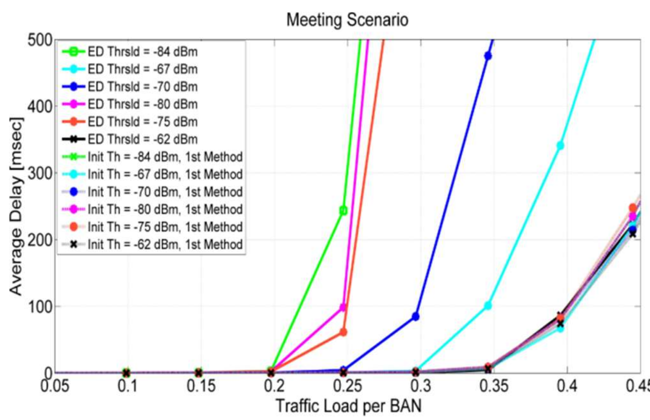

Figure 3. Average Packet Delay vs Traffic Load for the Meeting Scenario

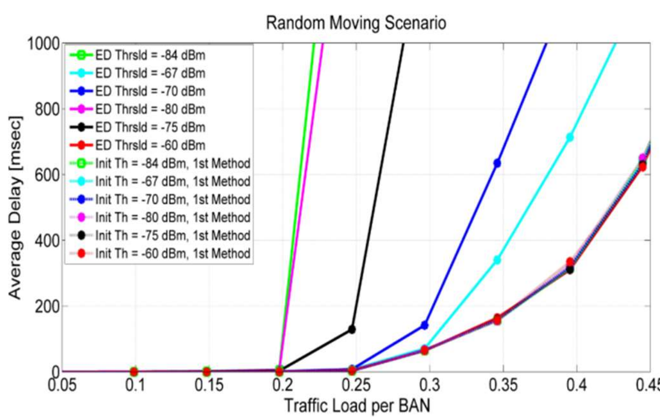

Figure 4. Average Packet Delay vs Traffic Load for Random Moving Scenario

The average packet delay performance obtained using all the adaptive ED threshold schemes described in Section II for both meeting and random moving scenarios have been presented in Figure 5. The results achieved by adaptive schemes ‘B’ (i.e. sliding window) and ‘C’ (moving average) are very close to those obtained by using adaptive scheme ‘A’ for both scenarios.

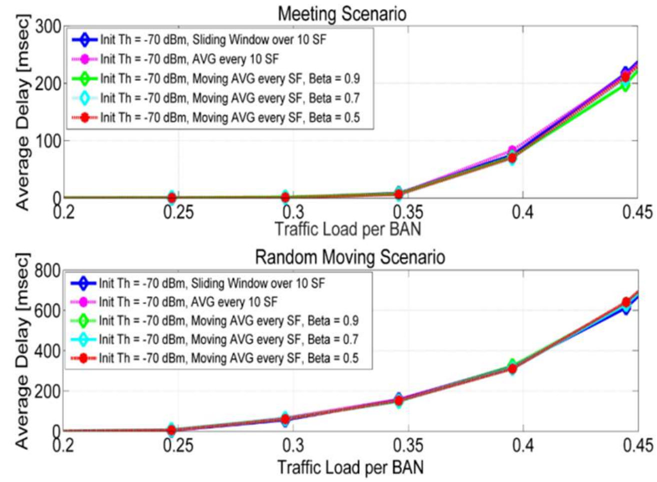

Figure 5. Average Packet Delay vs Traffic Load for different adaptive strategies

Figure 5 also highlights the performance of the moving average scheme under three different values of β. Although the results show that the difference is minimal further studies are required to determine if there exist an optimal value for this parameter.

To measure fairness among the links in each multi-BAN scenario, we have also defined the following metric:

$$Std\left(\frac{Average\ Queue\ Size\ at\ Transceiver\ i}{Average\ Interference\ at\ Transceiver\ i}\right)$$

where $Std(.)$ denotes the standard deviation of the ratios of the average queue size at each transmitting node to the average interference that the node has experienced. This metric, which conveys a notion of proportioanl fairness, is intended to represent fair access to the channel given the level of interfernece that the transmitting nodes are experiencing. Note that smaller values of this standard deviation indicate higher degree of fairness among competing transmitters. Figure 6 displays this fairness metric for both meeting and random movement scenarios. Higher traffic load corresponds to higher overall inter-BAN interference and as observed the gain in fairness metric is more pronounced for higher traffic loads. The ability of the ED threshold adaptation to ensure graceful performance deterioration under high inter-BAN interference is specially important for medical applications that have stringent reliability requirements. For the stationary meeting scenario, all adaptive schemes seem to have an excellent fairness performance regardless of the traffic load.

So far it has been assumed that the queue size at each node is infinite; therefore the backlogged packets can stay in the queue until they finally get an opportunity to be transmitted. However, most applications (especially medical) require bounded latency for data packets. We have also investigated the performance of our proposed adaptive ED threshold schemes considering an expiration time of 250 msec for the packets. This value has been cited as the required maximum Peer-to-Peer latency for most commonly used BAN medical applications [9].

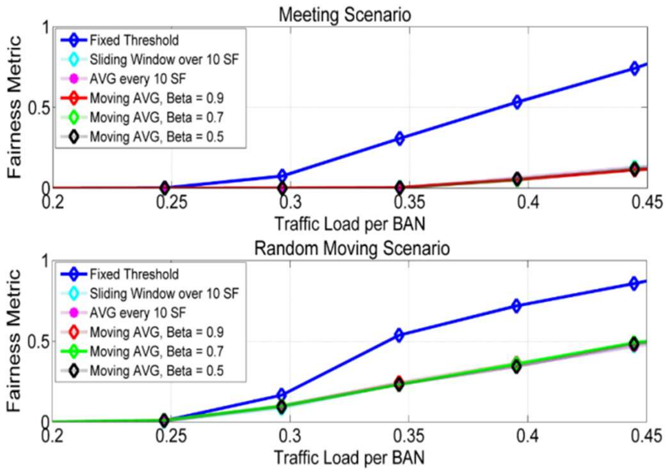

Figure 6. Fairness for Meeting and Random Moving Scenario with different adaptive strategies

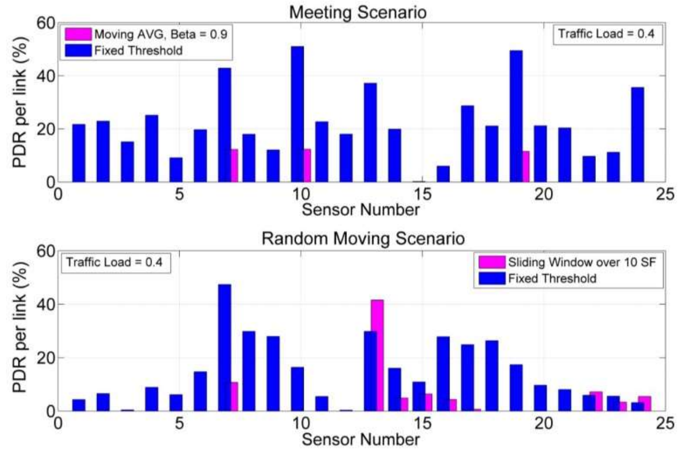

Figure 8. Histogram of the PDR per link for meeting and random scenarios (traffic load=0.4)

Considering a maximum packet latency of 250 msec, Fig. 7 shows the average packet drop rate per link versus traffic load for the meeting and random moving scenarios using static and adaptive ED thresholds. As observed, for the random movement scenarios, the PDR with the weighted average strategy improves over 50% when traffic load exceeds 0.3. The PDR gain in the meeting scenario is even more significant. Not only the average PDR performance across all links is better with the adaptive ED threshold scheme but also the standard deviation of the PDR per link is much lower. This is evident by observing the histogram of PDRs per link for a given traffic load means in Fig. 8. The adaptive schemes lead to a much fairer channel access to all nodes of the system. Similar comparisons were also done for other adaptive strategies outlined in Section II and the performance results were essentially identical.

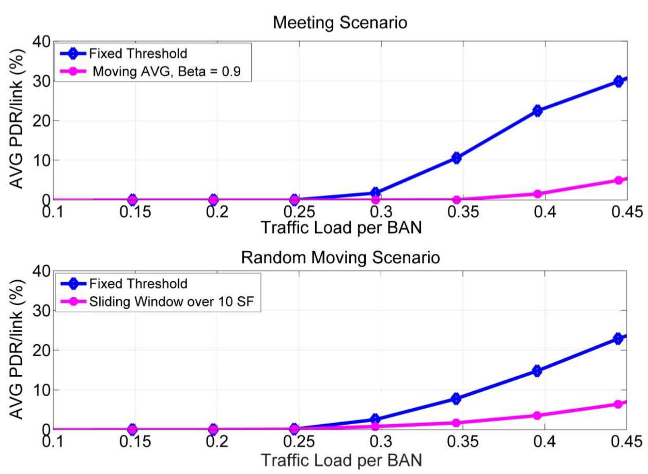

Figure 7. Packet Drop Rate vs Traffic Load for Meeting and Random Moving Scenario

V. CONCLUSIONS & FUTURE PLANS

This paper proposes several low complexity adaptive schemes that can help to mitigate inter-BAN interference and enhance performance across all links in a system composed of multiple adjacent body area networks. Compared to the common static ED threshold, our simulations suggest that these simple strategies result in significant improvements in average packet delay, packet drop rate and fairness. These performance gains could justify the small additional complexity that is required to process the measured interference across several SFs. Although the performances of the three proposed methodologies were very close, the choice of the best strategy could be dependent on the exact usage scenario, and the desired performance metric. More detailed studies are needed to optimize the parameters involved in our proposed schemes i.e. the number of SuperFrame to sense or measure interference or the weighting factor β.

Authors are also investigating more sophisticated adaptive strategies where information such as channel condition and queue size will be taken into account to adjust the ED threshold. Although, higher gain might be achievable, the trade-off will certainly be more complexity in terms of implementation and therefore energy usage. The ultimate goal of our efforts is developing practical recommendations for implementation or modification of the IEEE 802.16.5 standard.

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